Building and Environment 207 (2022) 108497

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Seasonal influence of leaf area index (LAI) on the energy performance of a green facade

Gabriel Pérez [a,*], Julià Coma [a], Marta Chàfer [b,c], Luisa F. Cabeza [b]

[a] Department of Computer Science and Industrial Engineering, Universitat de Lleida, C/Jaume II 69, 25001, Lleida, Spain
[b] GREiA Research Group, Universitat de Lleida, Lleida, Spain
[c] CIRIAF - Interuniversity Research Centre, Perugia, Italy

ARTICLE INFO

Keywords:
Urban green infrastructure
Vertical greening systems
Normalized difference vegetation index (NDVI)
Passive energy saving
Building
Shadow effect

ABSTRACT

Double-skin green facades using deciduous climbing plants are easy-to-implement construction systems stated to be effective energy-saving tools for buildings during cooling periods. Although the leaf area index (LAI) has been identified as a key parameter for characterizing foliar density and, consequently, the green facade's potential as a passive tool for energy savings, a lack of knowledge still remains on this index's values and measurement methods. The present paper aims to characterize the annual LAI evolution of a Boston ivy double-screen green facade under Mediterranean continental climate (Csa), by using an original non-destructive methodology during two consecutive years. Moreover, the influence of the green facade's foliage density, characterized by LAI, on the external building wall temperatures and the energy consumption by season and orientation was addressed. From the results it can be noticed that LAI changed seasonally over the course of five periods with a related differentiated energy performance: early summer (LAI of 4.8; 54% savings for cooling), late summer (LAI of 4.4; 30% savings for cooling), autumn (LAI of 1.7; 5.4% increase for heating), winter (LAI of 0.9; 5.4% increase for heating), and spring (LAI of 3.6; 11.9% increase for heating). The increase of energy consumption during leaf-off stage was directly linked to woody material and remaining leaves. Two crucial effects were identified and characterized: firstly, the influence of facade orientation and, secondly, a slight "insulation effect" at night, with the green screen acting as a thermal barrier.

1. Introduction

The building sector is currently facing major challenges in order to reduce its environmental impacts and achieve the stablished sustainable development goals for the nearby future [1]. Among other challenges, such as reducing waste production and materials consumption, the need to reduce energy consumption, especially during the operational phase of buildings, stands out [2].

The integration of vegetation in the building's skin is an interesting strategy that not only reduce the energy consumption of the building, but also provides multiple benefits. At the building level some of these benefits are the sound insulation capacity, the protection of internal materials, the rainwater capture, the food production, the improvement of aesthetic value, as well as, it reduces the heat island effect, the capture of CO2 and pollutants, the runoff control, among others at the city level [3,4].

More specifically, it can be highlighted the high capacity to reduce the energy demand of buildings by applying vegetation on the facades (Fig. 1). In previous research, it was demonstrated that VGS can passively reduce the energy consumption of a building by up to 34% during the cooling period, in the case of a double-skin green facade, and up to 59% in the case of a green wall in a Mediterranean continental climate [5]. Also under humid subtropical climates a summer cooling energy reduction of 11–31 kWh for every m^2 of green façade was reported [6].

When it comes to the impact of vertical greenery on a building's thermal performance, it is important to consider that the construction differences between VGS can lead consequently to different thermal behaviour once applied to the building envelope. Table 1 shows an updated general classification of VGSs and their main characteristics [7,8]. The research presented in this article focuses on green facades, and specifically on a double-skin green facade using a light mesh that supports a very vigorous deciduous climbing plant, widely used around the world, known as Boston ivy.

* Corresponding author.
E-mail address: gabriel.perez@udl.cat (G. Pérez).

https://doi.org/10.1016/j.buildenv.2021.108497
Received 28 June 2021; Received in revised form 17 September 2021; Accepted 24 October 2021
Available online 27 October 2021

Regarding the passive energy saving potential of these systems, Pérez et al., 2014 [7] classified the main operating methods of VGSs into four different effects: the shade effect, the cooling effect, the insulation effect and, finally, the wind barrier effect (Table 2).

As shown in Table 2, the most influential variable is the leaf area index (LAI), influencing all the effects involved in the thermal behaviour of a green facade. By defining the amount of biomass in a canopy, LAI becomes a key parameter for estimating the potential cooling effect of a green facade, providing shade and consequently energy savings, or to evaluate the potential restrictions of evergreen vegetation in heating periods.

In agreement with this idea, some previous authors have highlighted the importance of LAI as a descriptor of a green facade's leaf density [9–14]. In their studies they have tried to establish a value for the LAI, but as can be seen in Table 3 there is great dispersion and even confusion in the assignment of values to this variable. This is a transcendental fact, since LAI represents a key piece in calculating the influence of green facades on passive energy savings, any error in its measurement and/or estimation can compromise the results obtained. Table 3 summarizes the most prominent studies in which an attempt has been made to measure, or at least assign a value to, the LAI. The main weaknesses of these values can be summarized as:

- Dispersion of values.
- There is a lack of a clear and easy-to-apply LAI measurement methodology for green facades.
- Isolated LAI measurements, which do not describe variations in LAI throughout the year in deciduous plants.
- Most of these studies only focused on cooling periods, underestimating not only the consequences of the green layer on the

Fig. 1. Examples of different vertical greening systems (VGS). Green facades (GFs): a) traditional; b) double-skin; c) perimeter flowerpots. Green walls (GWs): d) geotextile-based; e) panel-based. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

thermal behaviour of the building during the winter season (heating period), but also its influence through the transition periods between cooling and heating seasons.
- Some studies only estimated LAI using references from agriculture or forestry, far from the urban building context of green facades.

By reviewing the previous researches, it is noteworthy that only few studies have experimentally studied how a green facade can influence the thermal behaviour of a building, the most outstanding being those conducted by Pérez G. et al. in Refs. [15,16] and Lee L.S.H [10]. The authors emphasized that out of the effects presented in Table 2, shade is potentially the most influential when it comes to the final building energy demand. Thus, temperature reductions between 5.5 °C and 15.2 °C on a building wall were recorded as a direct consequence of the shade effect provided by a double-skin green façade [15,16].

These studies also highlighted the importance of establishing a relationship between plant foliage density, characterized by the leaf area index (LAI), and temperature reduction by orientation. In agreement with these results, further investigations, carried out under a humid-tropical climate (Cwa) [17], showed how solar radiation, facade orientation, and shading influenced the final contribution of plants to the whole thermal performance of the building, as well as the variation in the cooling effect in summer under sunny, cloudy, and rainy conditions.

More recent studies have also pointed to the importance of characterizing the leaf density of vegetation. Perez et al. (2017) [13] evaluated the shade capacity of a double-skin green facade to intercept the direct solar radiation on a building's east, south and west orientation with large foliage development (LAI of 3.5–4) under Mediterranean continental climate (Csa). High reductions in the external surface wall temperatures on all sides and consequently electrical energy savings of up to 34% for cooling periods were achieved. This study, in agreement with the results published by Jim C.Y (2015) [17], also pointed out that the amount of energy savings provided by the double-skin green facade in summer is dependent on the orientation. Thus, in that research maximum reductions of the building surface temperature of −15 °C on the east facade (from 36.4 °C to 21.4 °C at 12:15 h, keeping it below 23 °C all day long), −16 °C on the south facade (falling from 46.7 °C to 30.7 °C at the time of peak temperature on this orientation, at 15:45 h) and −16.4 °C on the west facade (dropping from 43.9 °C to 27.5 °C at 19:00 h), were observed [14].

However, these LAI measurements conducted by Pérez et al., in 2017 [13] were performed manually at a specific time in plant development. Therefore, they encompass neither the growth and fall cycles of the vegetation nor the winter season. The lack of this information could have a major influence on the annual thermal behaviour of a building, especially when deciduous plants are selected for a double-skin green facade.

But a crucial concern is what happens during transition periods, that is spring and fall seasons, in which "falling and grow" processes duration depends on the type of plant and annual climate conditions. In addition, these processes usually take place at the same time that the heating period is shifting to the cooling one, and vice versa. In a forerunner research study, the influence on the shade effect of the leaf growth and fall of three different climbing plants was studied [18]. The results underscored the high influence of transition periods on solar gains, during spring and autumn, and therefore on the thermal behaviour of the whole building.

According to the considerations above and in view of the lack of experimental data on the characterization of a green facade's continuous annual LAI evolution, a two-year study was proposed to measure not only the seasonal evolution in leaf density but also its consequences on the thermal behavior of the building.

Although main goal of the study was to establish the seasonal evolution of foliar density (LAI) by building facade orientation and its seasonal capacity to intercept solar radiation (shade effect) under Mediterranean continental climate (Csa), a secondary aim of this study was to look for an appropriate and generalizable methodology to measure and characterize continuously LAI on green facades (vertical plane).

Thus, the paper is structured to cover three main objectives: (1) to look for, test and define a universally replicable methodology for continuously measuring the vertical leaf area index (LAI) of any VGS by using a non-destructive process; (2) to characterize the annual LAI evolution of a double-screen green facade made up of a Boston ivy deciduous climber plant (*Partenocissus tricuspidata*) under Mediterranean continental climate (Csa, warm temperate - summer dry - hot summer);

Table 2
Operating methods and main variables influencing the thermal behaviour of VGSs and their performance on the building envelope.

Effect	Method	Potential variables
Shade	Direct solar radiation interception provided by plants and support structures	• Leaf Area Index LAI (foliage density) • Facade orientation • Substrate thickness, composition and moisture
Cooling	Evapotranspiration from the plants and substrates	• Leaf Area Index LAI (foliage density) • Type of plant (transpiration coefficient) • Climate conditions (dry/wet) • Wind speed • Substrate thickness, composition and moisture
Insulation	Insulation capacity provided by materials and layers: plants, air gap, substrates, felts, panels, etc.	• Leaf Area Index LAI (foliage density) • Air gap thickness • Substrate thickness, composition and moisture
Wind barrier	Capacity of plants and support structures not only to modify the direct wind effect on the building facade walls but also to remove air from the VGS's internal layers	• Leaf Area Index LAI (foliage density) • Facade orientation • Wind speed and direction

Table 1
Vertical greening systems and their main characteristics.

Vertical Greening Systems (VGSs)		Main layers				Maintenance
		Support structure	Air gap	Substrate	Plant typology	
Green facades (GFs)	**Traditional**	Without support. Directly on the building facade	No	No	Climber plants	Extensive
	Double-skin	Very light, steel wires or mesh	Yes, usually open	No	Climber plants	Extensive
	Perimeter flowerpots	Flowerpots	Yes, usually open	Yes, filling the pots	Climber and hanging shrubs	Intensive
Green walls (GWs)	**Geotextile**	Geotextile felts supported by light frame structures anchored to the building facade	Without or the frame space	No or inside the pockets	Shrubs and hanging shrubs	Intensive
	Modular panels	Plastic panels supported by frame structures anchored to the building facade	Yes, open or closed	Yes, filling the modules	Shrubs	Intensive

Table 3
Previous research highlighting LAI as a key variable when studying the green facade as a passive tool for energy savings in buildings.

Year	Authors	Plant	Plant typology	LAI	Method
2019	Suklje T. et al. [9]	*Phaseolus vulgaris* L	Annual plant not suitable for green facades	6.1–7.2	Ten isolated measurements using Li-Cor LAI-2200
2019	Lee L.S.H and Jim C.Y [10]	*Lonicera japonica*	Deciduous	0.24	Isolated destructive leaf harvesting
2018	Vox G et al. [11]	*Rhyncospermum Jasminoides*	Evergreen	2–4	AccuPAR PAR/LAI Ceptometer (model LP-80, Decagon Devices Inc., Pullman, WA, USA)
		Pandorea jasminoides Variegated	Evergreen	1.5–3.5	
2018	Poddar S et al. [12]	Hereda helix	Evergreen	May = 3.66, July = 2.78, October = 4.29, and February = 3.72	Adapted from a previous study by Pitman and Broadmeadow, 2001
2017	Pérez et al. [13]	*Partenocissus tricuspidata*	Deciduous	2.1–3.9	540 measurements in three orientations and three levels using the PAR Sunfleck Ceptometer
2013	Susorova I. et al. [14]	-	-	0.01 for short plants with small leaves, to 3 for leafy shrubs, and to 7 for a dense forest canopy	Not measured, extracted from bibliography (Sinbank W.C. 1968)

and (3) to evaluate the influence of the green facade's foliage density, characterized by LAI, on the external building wall temperatures and the energy consumption by season and orientation (east, south and west facades).

2. Materials and methods

As highlighted in the introduction, the continuous annual LAI evolution of a building green facade has never been measured before. The continuous measurement of LAI is a common practice in the field of agriculture (horizontal plan) with the aim of monitoring crops during their growth. This research aimed investigating the application of these techniques, in the vertical plane, for the measurement of the continuous LAI in green facades of buildings (vertical plane).

This section first introduces the fundamental concepts related to LAI measurement and related parameters. These concepts, although widely known in the field of agriculture, they are not usually used in other areas of knowledge, such as building sector. Then, the experimental set-up and the green facade used to conduct the measurements is described in detail. Finally, the original methodology to continuously measure the LAI, adapted to the vertical plane, is explained.

2.1. Leaf area index. Concepts and measurement

2.1.1. LAI concept

The leaf area index (LAI) is a dimensionless value that makes it possible to characterize canopies' foliage structure and density. LAI has been extensively used in agriculture and forestry to estimate the growth and yield of crops as well as the mass (biomass), water and energy balances in forest ecosystems [19,20].

For broadleaf plants, LAI is defined as the one-sided green leaf area per unit ground surface area (LAI = leaf area/ground area, m^2/m^2), its value ranging from 0 to 10 depending, basically, on the plant's typology and growth phase [19].

Despite being the most reliable "direct method", LAI measurement implies the manual collection and further individual measurement of all the leaves in one square meter of plants. Meanwhile, "indirect methods" are approaches to the real value of LAI based on the relationship between light extinction through the canopy and the related foliar density (LAI) [21].

The application of the LAI concept is very interesting in the urban green infrastructure (UGI) field since it makes it possible to measure the density of the foliage (biomass), one of the most influential variables not only when it comes to providing passive energy savings in buildings but also in reducing the urban heat island (UHI) effect at the citywide level.

However, when the concept of LAI is used in vertical greening systems, it is necessary to consider the adaptations for its measurement in the vertical plane, since in current methods used in agriculture only the horizontal measurement is considered [13].

2.1.2. PAR vs. LAI

It is known that dry matter production of a plant canopy is directly related to the amount of photosynthetically useful radiation intercepted by the canopy (radiation in the 400–700 nm waveband, which represents the portion of the solar spectrum which plants use for photosynthesis). According to this relationship, one of the most widely used indirect methods to obtain LAI is the photosynthetically active radiation (PAR) inversion technique, based on the estimation of LAI using the amount of light energy transmitted by a plant canopy, so that the more leaf density the lighter absorption [22]. The PAR measured, by means of specific equipment such as a ceptometer, in a plant canopy is a combination of the radiation transmitted through the canopy and radiation scattered by leaves within the canopy [23].

Usually, this technique is based on multiple single measurements of LAI. Since in most plant canopies, the LAI varies across the space, researchers must consider spatial variability by developing a sampling scheme to gather the necessary measurements in order to obtain a representative value of the entire canopy.

2.1.3. NVDI vs. LAI

PAR inversion technique is a very useful method for characterizing the LAI of a developed crop through a set of single measurements. But when the goal is to characterize the temporary evolution of this index, e.g. in the case of deciduous plants whose LAI changes during the spring and fall seasons, this methodology has some limitations since it entails taking independent readings in a continuous way.

In this sense, the normalized difference vegetation index (NDVI) makes it possible to calculate the LAI continuously based on the canopy reflectance in red and near infrared (NIR) wavelengths.

Because automated sensors provide information about crop development and performance across time, ground-based canopy reflectance data is used to define crop phenology over the course of the season that can better forecast crop yield at harvest [24].

NDVI is based on the concept that vegetation reflects light differently in the visible spectrum (400–700 nm) than it does in the near infrared spectrum (>700 nm). Green leaves absorb light most strongly in the visible spectrum, especially at red wavelengths, but are highly reflective in the near infrared region. NDVI has been shown to correlate well with green LAI, although the relationship is crop, or canopy, specific [23,25].

As LAI increases, red reflectance will typically decrease due to increasing canopy chlorophyll content, whereas NIR reflectance increases due to expanding mesophyll cells and increasing canopy structural complexity. So, under typical field conditions, NDVI values typically range from somewhere around 0 to 1, representing low and high LAIs, respectively.

Specific sensors make it possible to measure canopy reflectance in red and NIR wavelengths, and their measurements can be used to calculate or approximate LAI. Red and NIR reflectance levels are used in the following equation (Eq (1)) to calculate NDVI [19,23]:

$$NDVI = \frac{\rho NIR - \rho red}{\rho NIR + \rho red} \quad (1)$$

where ρ denotes percent reflectance in NIR and red wavelengths.

To directly estimate LAI using NDVI values, it is necessary to develop a site-specific or crop-specific correlative relationship. For example, taking co-located measurements of NVDI and LAI (e.g. using a ceptometer) during a period of rapid canopy growth, and then developing a linear model, by means of a least squares regression, to directly correlate NVDI values with LAI.

The possibility of measuring seasonal LAI evolution is quite useful since it allows data to be provided at the following times:

- LAI values at the time of maximum plant development
- Evolution of LAI during leaf growth and decrement
- Contribution of woody material during leafless stages

2.1.4. Concept of PAI

Plant area index (PAI). Some researchers refer to the measurement obtained from the LP-80 and similar instruments as the plant area index (PAI) rather than LAI, in order to acknowledge the contribution of non-leaf material to the measurement. It should come as no surprise that PAI will be higher than LAI in any given ecosystem. However, PAI and LAI values are often not too different because leaf area is generally much larger than branch area and the majority of branches are shaded by leaves. In deciduous ecosystems, the contribution of woody material can be accounted for by acquiring measurements during the "leaf-off" stage [23,26].

2.2. Experimental set-up and green facade description

The experimental measurements were taken from a fully consolidated double-skin green facade used in a previous study to measure the LAI and its relation to the shade effect in buildings located in Puigverd de Lleida, Spain [13,27].

This location has a Mediterranean continental climate (*Csa, warm temperate - summer dry - hot summer*, according to Köppen classification) [28] characterized by cold and foggy winters while summers are hot and dry. The mean annual temperatures oscillate between 12 and 14 °C, with daily thermal amplitudes of 17–20 °C.

The double-skin green facade covers the east, south and west facades of an entirely monitored cubicle. In order to characterize the seasonal LAI evolution and its thermal response, a second identical cubicle without the green coverage was used as a reference. The cubicles have internal dimensions of 2.4 × 2.4 × 2.4 m, and they were designed as presented in Fig. 2. The basement consists of a reinforced concrete slab of 3 × 3 m. The following layers describe the composition of the building's walls structured from inside to outside: plaster as internal coating, alveolar brick (30 × 19 × 29 cm), and an external protective coating made with mortar. Due to the insulation properties of the alveolar brick, no additional layer of insulation was required. The overall thermal transmittance of the building walls is 0.784 $W/m^2 \cdot K$.

The roof is made, from inside to outside, of: 8 cm of XPS, the structural roof slab made of precast concrete beams and ceramic floor arch of 25 cm of thickness, concrete relieved pending formation of 2% and a double waterproofing membrane. Externally this flat roof is finished with a single layer of gravel of 7 cm thickness.

The double-skin facade used in this experiment was made using a simple lightweight steel mesh supported through lightweight anchor bolts, placed 20 cm away from the building facade wall (Fig. 3).

Based on the research conducted to find the most suitable species to be used for green facades under Mediterranean continental climates [16], the plant species selected for the present experiment was Boston ivy (*Parthenocissus Tricuspidata*), which is a deciduous species well-adapted to this climate. Fig. 3 (below) shows the green facade development during the period of study.

With regard to maintenance activities, as showed in Table 1, double-skin facades based on climbing plants only need extensive maintenance which usually means to prune of foliage overgrowth and in some cases the provision of irrigation, depending on the plantation conditions (planters, directly to the soil, etc.) [29,30]. In the current research the plants were directly planted to the soil and consequently no irrigation was provided during the duration of this experiments. Only the leaves on the lower part of the façade were pruned, once a year, to keep the facade clean.

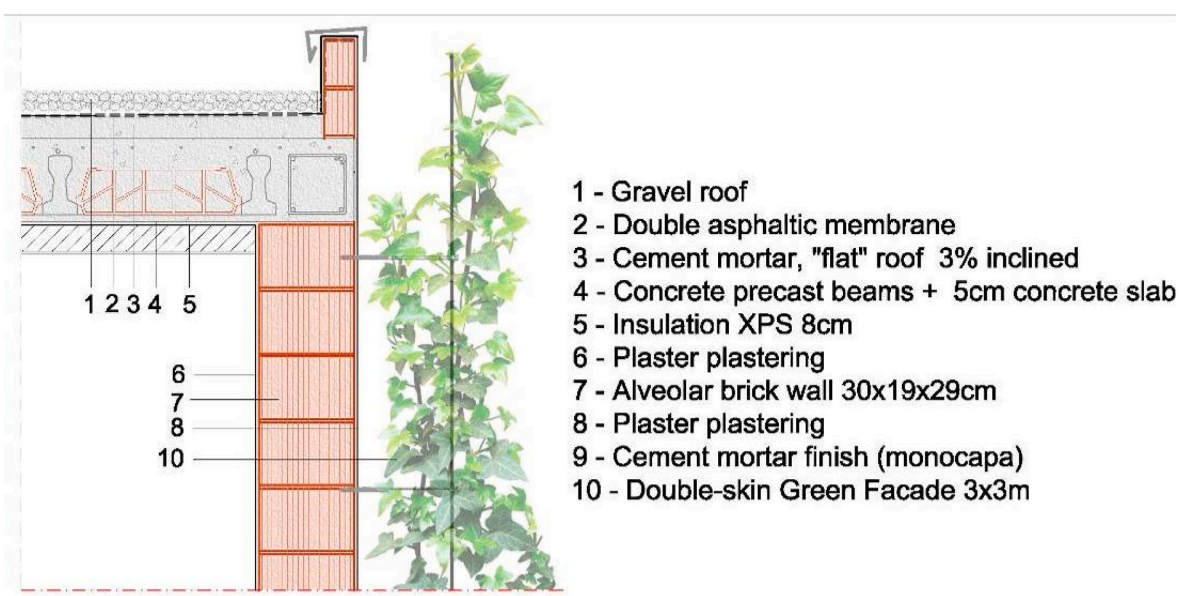

Fig. 2. Construction section of the cubicles used in the experiment.

Fig. 3. Installation process and details of the double-skin green façade (On top). Façade development during the period of study, from 2017 to 2019 (below). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

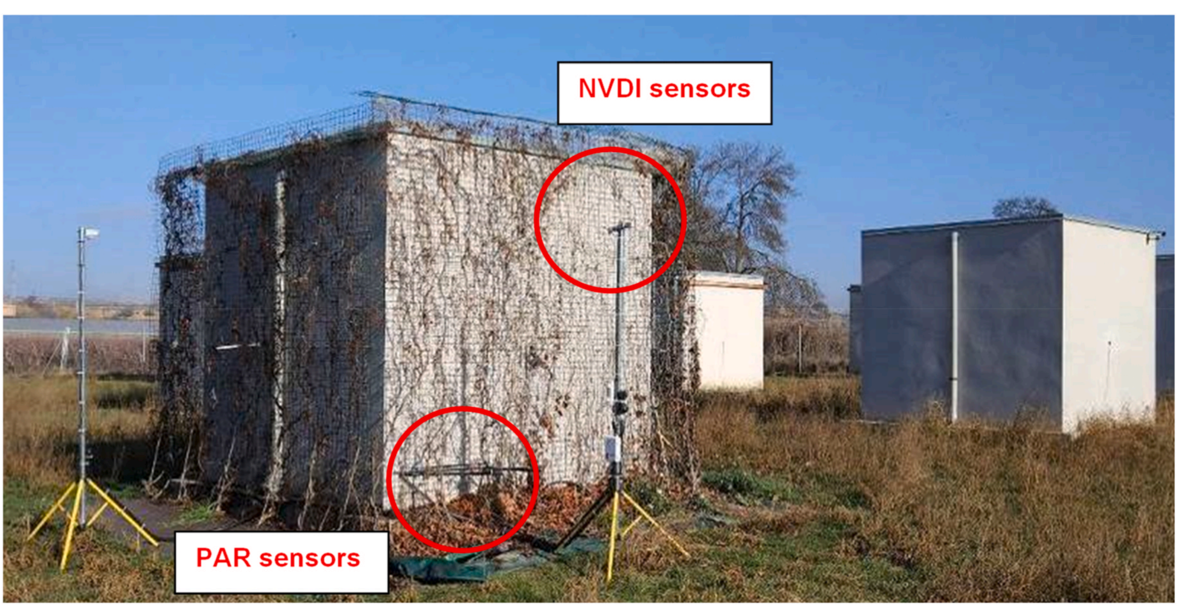

Fig. 4. Location of NVDI and PAR sensors.

2.3. Methodology used for LAI continuous measurements

In this research the methodology commonly used in the continuous measurement of LAI in agriculture on the horizontal plane, described in section 2.3.1, has been applied, for the first time, to a building green facade, on the vertical plane.

Thus to obtain an uninterrupted characterization of the LAI evolution of the double-skin facade, NDVI sensors were implemented on the east, south, and west facades. Then, to find the linear regression between NVDI and LAI, single measurements were collected with a ceptometer during periods of quick changes in the foliage, that is, in the spring and fall seasons. In addition, PAR sensors were located permanently on the south facade to gather additional data on the evolution of the foliage in this façade orientation and to be able to contrast the results

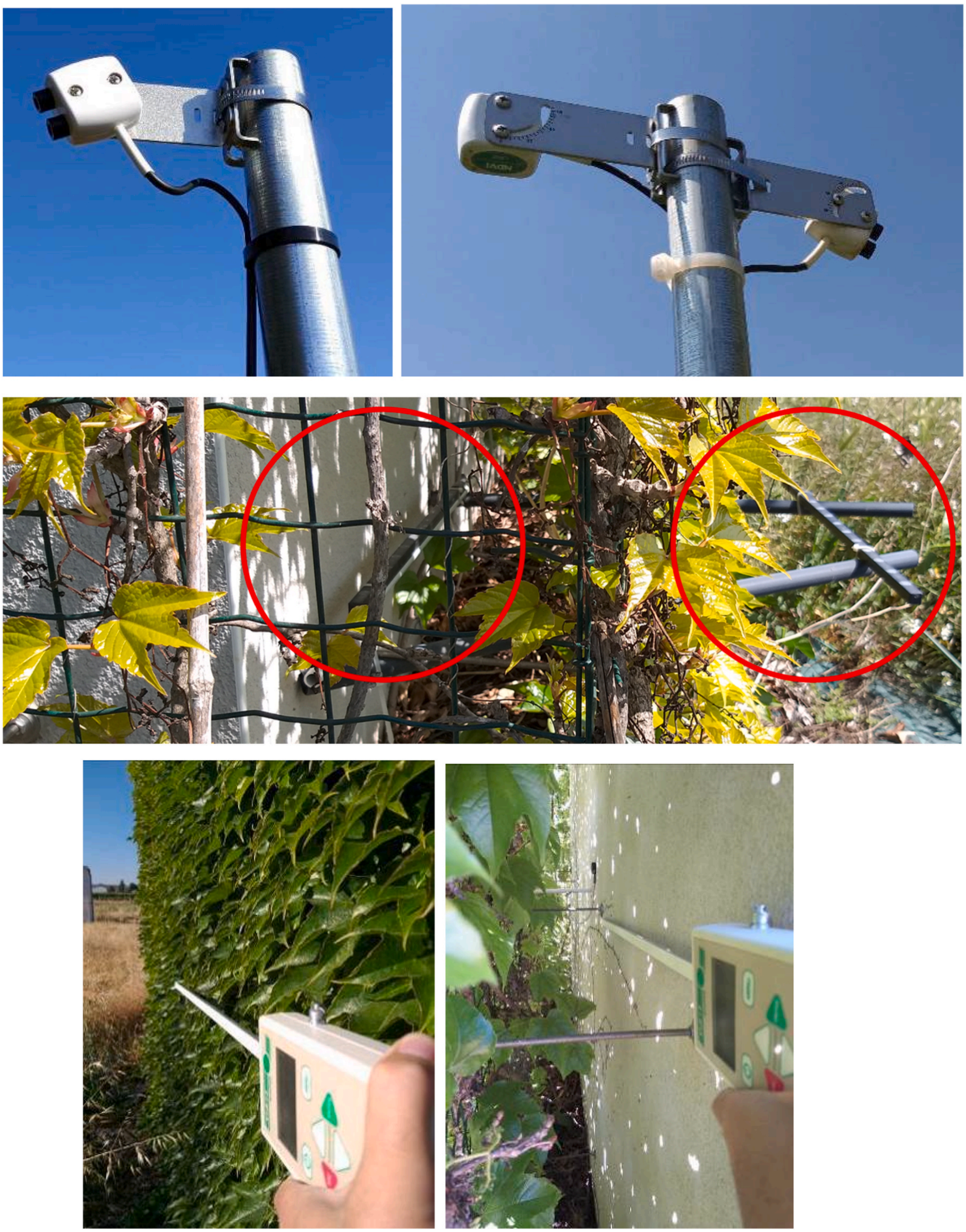

Fig. 5. SRS-NDVI sensors (on top); SQ-311 sensors placed on the south facade, in front of and behind the vegetation (middle); Manual measurement of LAI on the green facade using a ceptometer during spring and autumn 2019 (below). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with those obtained using the NDVI sensors (Fig. 4). The materials and methods used to measure NDVI and PAR are presented in the following sections.

2.3.1. Spectral reflectance sensors - normalized difference vegetation index (SRS-NDVI)

In order to continuously measure the NDVI in the double-skin green facade, the SRS-NDVI sensors (spectral reflectance sensors) were located at the appropriate height and distance away from the facade to generate a reading cone on the facade that can be representative of the entire surface [23].

The measurement set-up consists in four sensors, one having a hemispherical field of view, mounted facing toward the sky, and three others with a 36° field of view (18° half angle) mounted facing downward at the canopy (one for each orientation, east, south and west). Downward- and upward-looking measurements collected from each sensor are used to calculate percent reflectance in the red and NIR bands. Percent reflectances are used as inputs to the NDVI equation (Eq. (1)) (Fig. 5).

Technical specifications of SRS-NVDI sensors are: Accuracy: 10% or better for spectral irradiance and radiance values; Measurement Time <600 ms; NDVI Wavebands: 650 and 810 nm central wavelengths, with 10 nm full width half maximum band widths; Field of View: Hemispherical version: 180° full angle, Field stop version: 36° full angle (18° half angle); Operating Temperature: −40 to 50 °C.

In order to obtain the LAI value from the NDVI registered by each facade, specific single measurements of LAI were taken with a ceptometer (AccuPar LP-80. Decagon) during periods of quick changes in the foliage at the same time that NVDI was continuously being measured. In this way, a linear regression model could be established to obtain LAI values from the NVDI measurements (Fig. 5. On top).

2.3.2. PAR sensors

The main purpose of taking PAR measurements was only to provide additional data on the foliage's evolution throughout the year to later contrast the results with those obtained from the NDVI sensors, and therefore the results of these sensors will not appear in the results. PAR sensors were located on the south facade, in front of and behind the greenery (Fig. 5. Middle).

As mentioned above, the radiation that drives photosynthesis is called photosynthetically active radiation (PAR) and is usually defined as the radiation in the range of 400–700 nm. The PAR can be expressed as photosynthetic photon flow (PPF): photon flow in μmolm-2s-1 between 400 and 700 nm.

The sensors used were the SQ-300 Sun Calibration Line Quantum [31], specifically the SQ-311, with 10 sensors mounted in a row. These sensors provide average PPF measurements. All the sensors of the bar are connected in parallel, and as a result a single voltage signal is obtained that is directly proportional to the average PPF of the location of each individual sensor.

The main specifications of SQ-311 sensors used in the experiment are: Sensitivity: 0.2 mV per μmol m^{-2} s^{-1}; Response Time: Less than 1 ms; Field of View: 180°; Spectral Range: 410–655 nm: Operating Environment: −40 to 70 °C and 0–100% relative humidity.

2.4. Description of thermal measurements

The thermal response of the different cubicles studied was evaluated by means of the measurement of the following parameters, using a time record interval of 5 min:

- Surface temperatures of east, south and west walls (indoor and outdoor)
- The temperature of the air gap between the wall and green facade (east, west and south walls).
- Internal ambient temperature and humidity (at a height of 1.5 m).
- Internal floor and ceiling temperatures.
- Electrical energy consumption of the HVAC system.
- External ambient temperature and humidity.
- Global horizontal solar irradiance.

A solar pyranometer SK08-Middleton was used to capture the global horizontal solar irradiation. Pt-100 DIN B probes, calibrated with a maximum error of ±0.3 °C, were used to measure all the surface temperatures. The indoor air temperature and humidity used an ELEKTRONIK EE21FT6AA21 sensor (±2% accuracy). An electrical network analyser MK-30-LCD was selected to determine the electrical consumption of the HVAC systems (Fujitsu Inverter ASHA07LCC with cooling and heating capacities of 2.10 kW and 3.00 kW, respectively).

The experimental set-up allows working in both free floating and controlled inside temperature conditions. Although it is usual to analyse the evolution of indoor temperatures in free floating conditions for this specific study, which aims to evaluate the direct influence of green facade foliage density (LAI) on external building wall temperatures, the parameter ΔT is presented as the temperature difference between the equivalent surface on the reference and green facade cubicle. Previous studies have highlighted the importance of surface temperature as a key variable when analysing a green facade's capacity to provide energy savings in a building. This variable allows the results from different studies to be compared, regardless of the buildings' wall construction systems or climate conditions [7].

On the other hand, in order to measure the impact of double-skin facade LAI evolution on energy consumption, the electrical consumption of the cubicles was measured daily during specific periods of this study, covering all four seasons of the year and, therefore, both heating and cooling periods. For this purpose, the comfort conditions established in ASHRAE standard 55, which recommends temperatures of 20 °C to 25.5 °C for heating periods and 23 °C to 26 °C for cooling periods, were taken into account [32], and a set point of 22 °C for heating experiments, and 24 °C for cooling experiments, was established.

3. Results and discussion

3.1. Annual evolution of LAI in the green façade

3.1.1. Relationship between NDVI and LAI

As explained in section 2.1, a site-specific or crop-specific correlative relationship is necessary to correlate the LAI values and NDVI measurements. One way to evaluate this correlation is by taking measurements of NVDI and LAI during a period of rapid changes in the foliage density (growth or leaf-fall periods) and then by developing a square regression linear model.

To this effect, a set of manual LAI measurements were taken from the green facade, through spring and autumn 2019, by using a ceptometer, which directly calculates the LAI once the incident solar radiation has been manually recorded in front of and behind the vegetation cover (Fig. 5). These series of LAI measurements were correlated with the corresponding measured NVDI, for the same day and time, in order to obtain the ratio between these two values.

From the results of these measurements, a high correlation between the measured NVDI and LAI in the green facade was established according to the linear correlation shown in Fig. 6 (coefficient of determination of $R^2 = 0.94$).

3.1.2. Annual evolution in LAI

Fig. 7 shows the annual evolution in leaf density (LAI) on the studied double-skin green facade by orientation (east, south and west) for an uninterrupted period of one year and seven months, from 2 October 2017 to 20 May 2019.

For a better understanding of this plant evolution, it is necessary to take into account not only the plant species, Boston Ivy (*Parthenocissus Tricuspidata*), but also the climatology of both the macro-climate

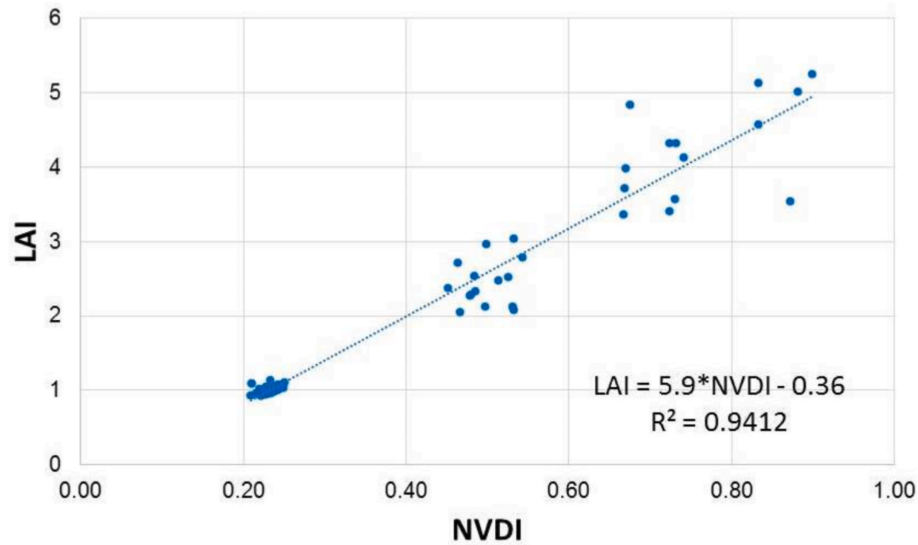

Fig. 6. Correlation between the continuous NVDI values and LAI.

(Mediterranean continental climate; Csa, warm temperate - summer dry - hot summer) and the local micro-climate.

Accordingly, five different periods could be clearly differentiated over the course of this study: early summer (full new leaf), late summer (degraded foliage), autumn (fall), winter (no leaves), and spring (growth). Fig. 7 also shows the plant development for each period.

Considering the starting point when the foliage is completely developed (summer period), specific LAI results by period and orientation are presented in the following subsections.

3.1.3. Early summer (full new leaf)

This period lasted about three months (May, June, and July) until the Boston ivy showed its maximum foliage development and, therefore, its maximum LAI values. The green facade reached peak LAI values between the range of 4.8 and 5, with small differences between orientations as shown in Fig. 7. The east orientation reached a larger development and, therefore, a higher mean value of 4.89, followed by the south (4.80) and west (4.74) orientations, respectively. It should be mentioned that at the location of this research experiment, the west and south orientations were conditioned by a steady south-westerly breeze that influenced plant development in comparison to the eastern orientation, which was protected from this breeze.

3.1.4. Late summer (degraded foliage)

At the end of July, with the increase in temperatures, low relative humidity and high solar irradiation, the leaves began to dry out and lose volume. In addition, the edges of many leaves were sunburned in some areas of the facade due to the aggressiveness of the summer weather conditions. During this period of approximately three months (August, September and October), the LAI decreased, and significant differences were observed between the three facades. The east facade maintained a mean LAI value of 4.74, on the west facade this index dropped to values of 4.42, and the south, perhaps the most exposed to the sun and the constant warm breeze, reached a mean LAI value of 4.13 (Fig. 7). In this period, the LAI values decreased, by orientation, from 4.80 to 3.49 on the south, 4.74 to 3.82 on the west, and 4.89 to 4.59 on the east green facade.

3.1.5. Autumn (fall)

Leaf fall occurred in November and December. It can be observed that, likely due to the annual climate conditions, there were some differences in the fall processes between the autumns of 2017 and 2018, the latter period being shorter and faster with lower mean LAI values by facade (Fig. 7). In terms of time, by mid-November 2018, the entire foliage had fallen, while in 2017, the leaves remained until almost January. As for LAI, in 2017, the LAI of the east facade fluctuated between 1.5 and 2, while in 2018, it dropped until values of one. On the south and west facades, LAI dropped between 0 and 1. It can also be observed how in the two fall seasons analysed, the west and south facades were more quickly defoliated than the east facade, a more protected side that retained the leaves longer.

3.1.6. Winter (no leaves)

The leafless period lasted from two to three months (January, February and March). During this time, the plant remained in the dormancy stage (Fig. 7). Although during this period, the LAI should have been close to 0, coverages between 0 and 1 were registered, or even higher, as was the case in winter 2017 on the east facade, with a mean LAI value of 1.71, varying from 0.91 to 2.35. This was the result of two main factors. On the one hand, there were branches that remained in the mesh throughout the year and increase their volume as the plants grew. On the other, there were old leaves which had failed to fall and remained on the plant throughout the winter period. This effect seems to be linked to the harshness of the autumn weather conditions, meaning that in the case of fall period of 2017, since it was less severe, the leaves did not fall (Fig. 7).

3.1.7. Spring (growth)

From mid-March, the plant began to activate and the foliage grew rapidly until reaching full development at the end of April. This process followed the same trend in the two monitored spring seasons of 2018 and 2019. Thus, during this very short period, the plant shifted from a LAI between 0 and 1 to a LAI of almost 5 (Fig. 7).

3.2. Influence of the LAI on the external wall surface temperature by facade orientation

The seasonal LAI variation described in the previous section has important implications for the annual thermal performance of a green facade. The amount of biomass, characterized by LAI, influences not only the green facade's ability to intercept solar radiation (shade effect), but also its transpiration (cooling effect), insulation effect, and capacity to reduce the wind effect (convection on the surface).

As explained before, in Pérez et al. (2014) [7] it was concluded that the external wall surface temperature of a building is the best parameter for comparing the thermal performance results of different vertical

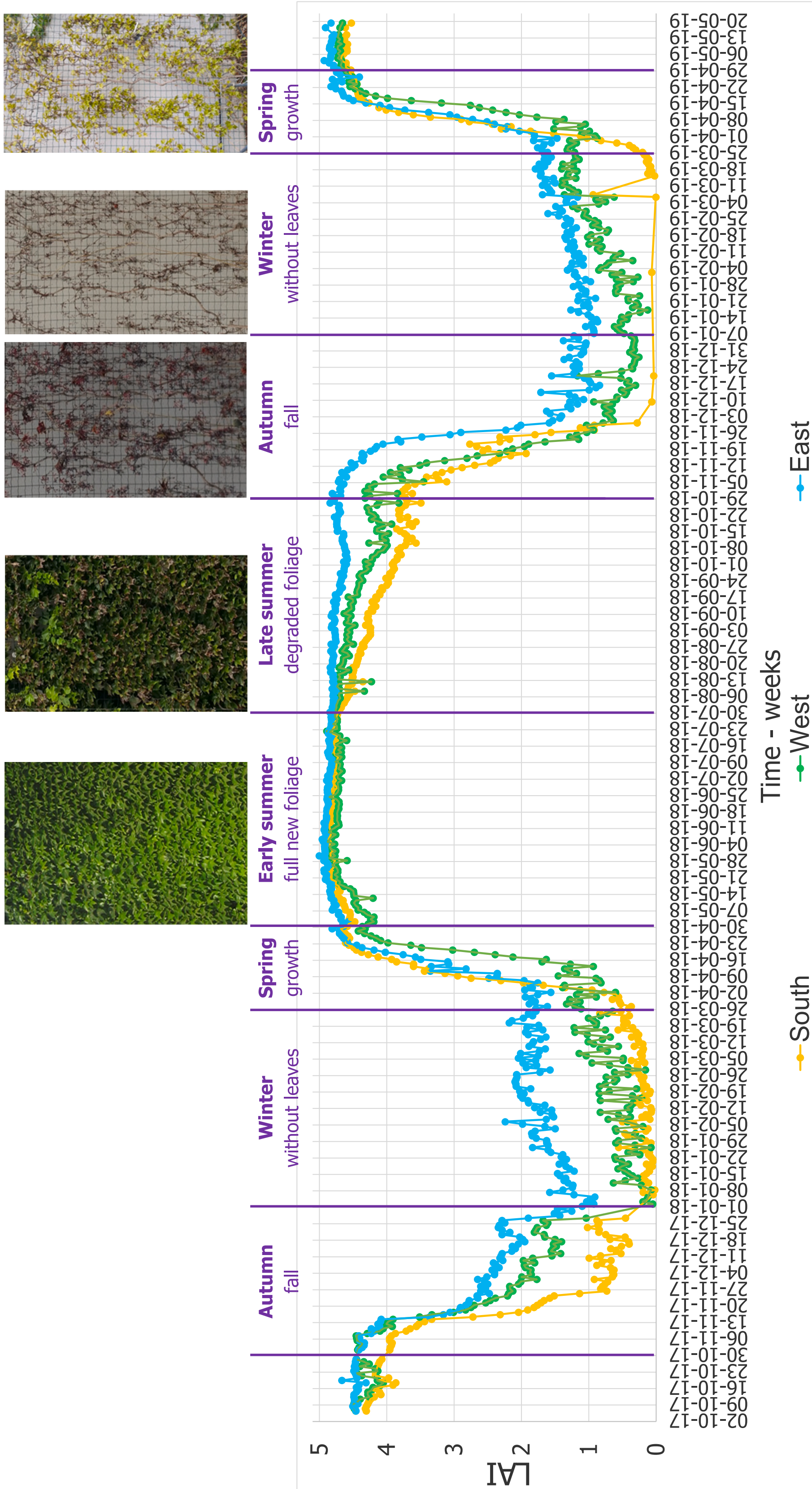

Fig. 7. Evolution in LAI on the studied double-skin green facade by orientation and foliage over the course of five different annual periods: early summer, late summer, autumn, winter, and spring. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

greenery systems. Thus, in order to characterize the seasonal influence of the LAI on the performance of the double-skin green facade under study, the external wall surface temperature of the building facades was monitored.

In the following sub-sections, all the figures will show the parameter ΔT, or the temperature reduction of the external wall surface by facade when the reference cubicle and the double-skin green facades are compared, as well as the daily LAI evolution.

The results are presented using the same five periods evaluated in Section 3.1.2 (Fig. 7): early summer (full new leaf), late summer (degraded foliage), autumn (fall), winter (no leaves) and spring (growth).

3.2.1. Early summer (full new leaf)

As explained in Section 3.1.2, this period lasted approximately three months (May, June and July) and the LAI values were close to 4.8 with small variations between the orientations.

Fig. 8 shows the evolution of the ΔT variable by orientation, which represents the capacity of the green facade to cool the external surface of the building wall in summer compared to a reference wall under free-floating conditions, so no HVAC system for cooling purposes was used. Fig. 8 shows 21 representative days for the early summer period with the LAI completely developed on the east, south, and west orientations. The highest daily temperature oscillation was 22 °C on 20 June (summer solstice), on the east facade.

Meanwhile, regarding the outer surface wall temperatures, the west facade of the reference building registered the highest temperature peak of 54.2 °C on 21 June (19:20 h) while the green facade cubicle reached its peak of only 35.4 °C at 19:10 h.

Besides the well-known temperature reductions provided by the double-skin green facade during daytime, is also important to characterize its daily negative values during summer nights. The observed negative ΔT values (Fig. 8), especially on the south and east orientations, mean that a fully-developed green facade acts as a thermal barrier (insulation effect) at night, preventing the surface of the building's facade from undergoing radiative cooling as quickly as on the reference cubicle, with no green facade. The negative peaks of ΔT were up to −3.6 °C (06:30 h), −2.0 °C (06:25 h), and −1.3 °C (06:45) on 6 July 2018 for the south, east and west orientations, respectively. This means that the surface wall temperatures of the double-skin green facade cubicle were slightly warmer than the walls of the reference cubicle at night. The lowest night time temperatures recorded in this period were 10.3 °C, 9.9 °C and 10 °C for the east, south and west sides of the green facade cubicle, and 9.0 °C, 8.0 °C and 9.6 °C, respectively, for the same orientations of the reference cubicle on 15 May 2018.

Since the construction system used for the facade wall, that is alveolar brick (30 × 19 × 29 cm), has a high insulating performance (overall thermal transmittance of the building walls is 0.784 $W/m^2 \cdot K$), this barrier effect on the radiative cooling has no incidence inside the experimental cubicle. However, it is worth to be taken into account in other climatic zones and when using other building facade wall construction systems.

In addition, Fig. 8 also shows the time of peak ΔT temperatures on the different facade orientations. As expected and as a consequence of the sun path, this effect took place first on the east facade, between 10:35 h and 11:25 h, later on the south facade, between 15:05 h and 16:15 h, and finally, around 18:45 and 19:35 h on the west facade. Summing up, the east and west facades exert a greater influence on the overall thermal performance in the sunny early summer period.

The energy benefits regarding the LAI values of the current Boston ivy have been experimentally calculated by using a heat pump system in both cubicles to set the ambient indoor temperature at 24 °C for cooling purposes through 13 uninterrupted summer days as shown in Fig. 9.

In this experimental set-up, the results confirmed that a LAI close to 5 [m^2/m^2], as is produced in early summer, can provide mean daily electrical energy savings of 54%. This is a very remarkable result because when the leaves are fully developed, the contribution of the green facade to the passive saving of energy for cooling is very high, as this period covers at least three months of the year (May, June and July) under the climate of study. Recent studies on the overheating risk in Mediterranean residential buildings have concluded that a general increase in cooling demand (up to 137%), but a smaller reduction in heating demand (up to 63%), can be expected by 2050. In this context, the use of VGSs that passively contribute to energy savings during cooling periods stands out as a very promising strategy which merits further study [33].

In terms of maintenance of the green facade, and at view of the obtained results in the current research, activities could be directed

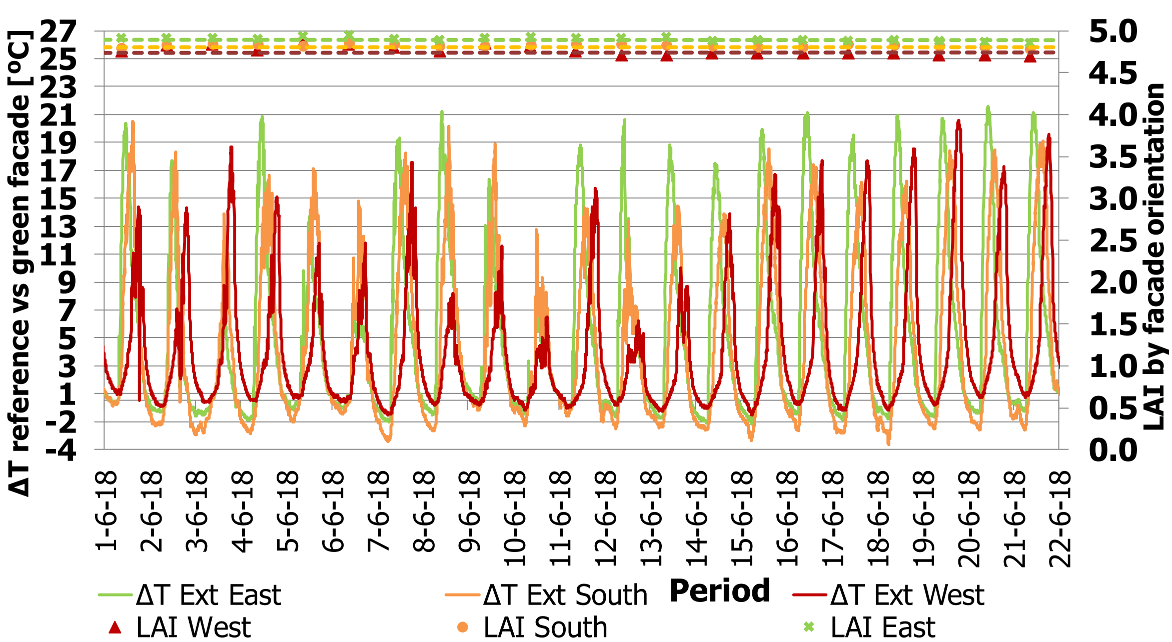

Fig. 8. The LAI evolution and temperature difference (ΔT) between the reference and the green facade systems in the early summer period of 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

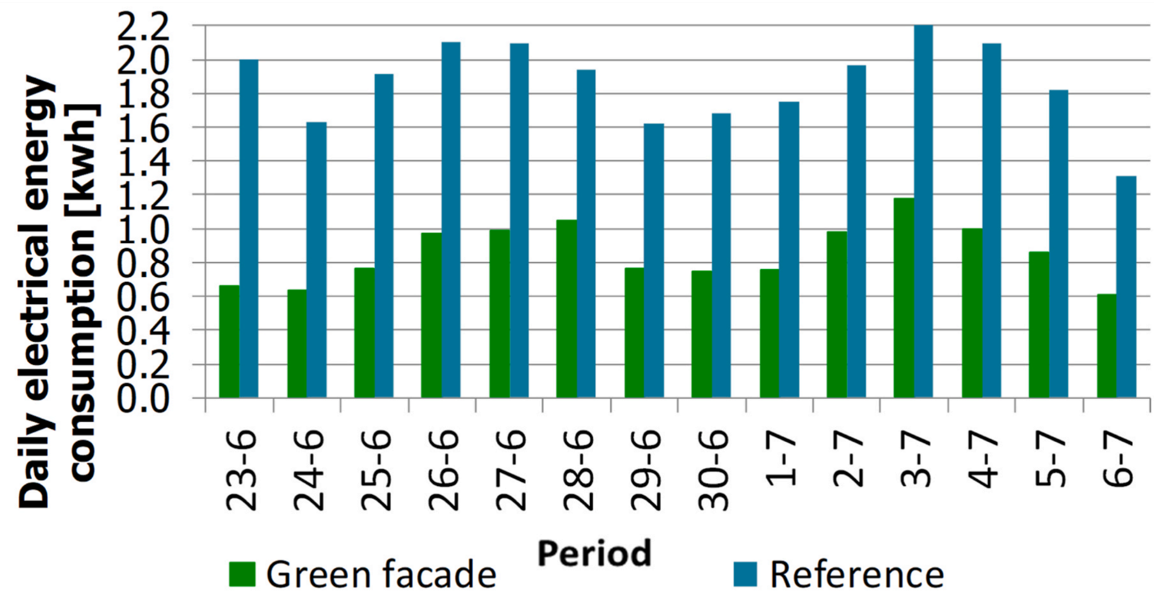

Fig. 9. Daily electrical energy consumption of the heat pumps at 24 °C. Early summer period of 2018.

towards the achievement of the maximum foliage density (LAI), by means of providing extra irrigation and some nutrients, if necessary. As Riley B. stated (2016) by reviewing the fututre of green walls, irrigation and preventive maintenance are key aspects for the success of vertical greening systems, not just for to guarantee a good aesthetic appeal but to optimize the provision of co-benefits, such as the shadow effect [34].

3.2.2. Late summer (degraded foliage)

The late summer period lasted around three months (August, September and October), and the LAI values started to decrease at different rates depending on orientation. Fig. 10 shows a representative period for late summer conditions and the evolution of ΔT by orientation.

Whereas LAI remained close to mean values of 4.72 on the east orientation, the index on the west facade dropped from 4.75 to 3.82 with a mean value of 4.42. Finally, the foliage in on the south facade was the most sunburned because of the lower solar angle (53.28° - 14:00 h) in comparison to the early summer period (71.88° - 14:00 h). The LAI values on the south facade decreased from 4.67 to 3.49 showing a mean value of 4.12 for the late summer period.

It is worth highlighting that, although the vegetation on the south facade was the most affected by the sun and showed the lowest LAI values, it was the most representative facade in terms of performance during this period. On the one hand, peaks of temperature reduction (ΔT) of up to 26.3 °C (12 October 2018) were obtained on the south facade when the reference cubicle was compared to the double-skin green facade. The east and the west facades showed peak temperature reductions of about 20 °C and 19.2 °C, respectively. On the other hand, the negative ΔT values by facade were in the same order, that is, south, east and west, the peak values being −6.2 °C, −2.5 °C and -2 °C,

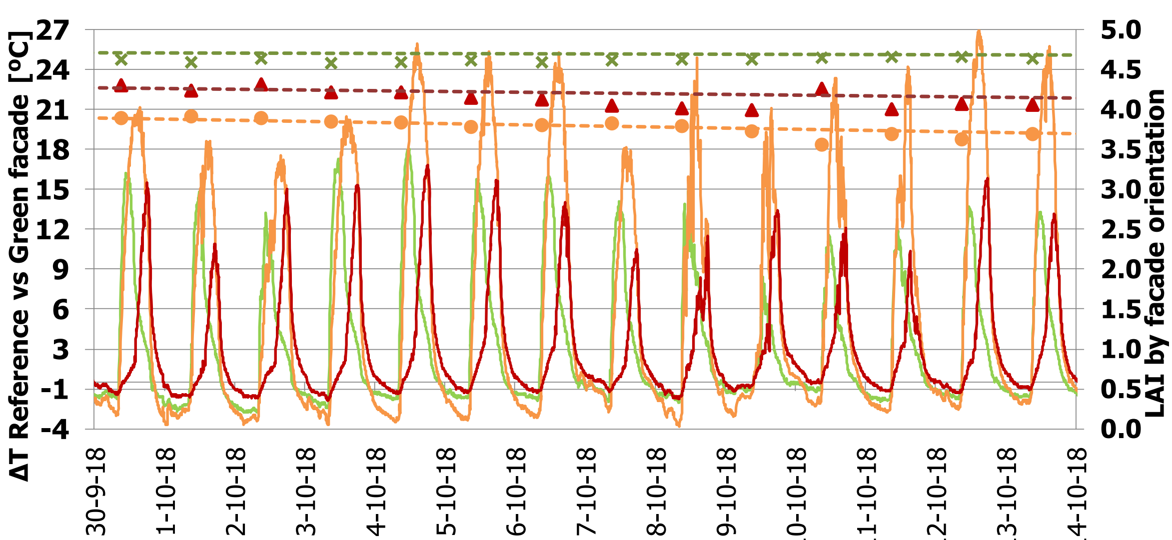

Fig. 10. The evolution of LAI and temperature differences (ΔT) between reference and green facade systems in the late summer period 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

respectively, which means the south orientation contributed more significantly to the insulation effect (thermal barrier) leading the building facade wall to cool slowly during the night period. Although it can be clearly observed, being a small effect, the construction system used, based on alveolar bricks, allowed it to be absorbed and had no consequences on the cubicle indoor temperatures.

Regarding the contribution of vertical greening to passive energy savings, Fig. 11 shows the daily electrical energy consumption of both the double-skin green facade and the reference cubicle for the late summer period, under an indoor set point of 24 °C, for cooling purposes. The representative 13 days, encompassing the end of August and a few days of September 2018, evaluated the potential passive energy savings in this period.

The mean daily electrical energy savings during this "late summer" was 30%, a figure in line with those obtained in previous studies on the cooling effect of the same green facade, being 33.8% in the 2015 study [13] and 34% in the 2017 study [5].

In addition, it is necessary to emphasize the difference that can be observed between this value of 30% during the late summer in reference to the value obtained in the previous period, the early summer, which was 54% in daily energy savings. This fact is remarkable because it implies that at the time when the leaves are more developed, green and active, their contribution is greater than when they begin to burn and harden due to the effect of the sun and the weather. This fact is very important as it makes it possible to consolidate a pattern of thermal behavior for the green facade which is repeated annually, therefore reducing the uncertainty these green systems often produce in terms of the provision of their functionalities (benefits).

3.2.3. Autumn (fall)

During November the leaves of Boston ivy start falling in the studied climate (Fig. 7), a process which lasts for three months coinciding with the change from the cooling period to the heating period in buildings in the studied climate. This natural process has great implications for the thermal performance of the double-skin green facade. Regarding the LAI trend by facade, the east orientation showed the highest mean value of LAI with 2.3, followed by the west (1.4) and south (1.0) (Fig. 12). Despite the differences in the absolute LAI values by facade at the beginning of this period, the slopes of the calculated linear trends for LAI showed that leaves fall at the same rate on all orientations. This calculation of slopes being an approximation, it can be seen that on the east facade the leaves tend to last longer, until the end of November, while in the south and west they progressively fall.

Based on the experience gained in the micro-climatic conditions at the study site, it can be stated that this fact is a consequence of the existence of a constant south-westerly breeze that causes the leaves to fall in these two orientations. The east facade is protected from this breeze and therefore holds the leaves longer. This wind effect was already characterized in previous studies [5,13].

This fact highlights not only the importance of considering the orientation of green facades but also the influence of the microclimate in each individual architectural project when working with construction systems to integrate greenery in the building envelope.

On the one hand, the south facade registered the highest temperature differences in comparison to the east and west facades in autumn season. The main explanation is the low sun path angle (25.05°) on the autumn solstice (23 September 2018), which has a more prolonged and perpendicular impact on the south than on the east and west facades. The temperature differences on the south wall ranged from approximately 26 °C during the first week of November 2018, when LAI values were around 3, to daily differences of around 12 °C at the beginning of December, with LAI values near 0. On the other hand, the east and west orientations with LAI values around 4.5 and 3.7, respectively, showed thermal amplitudes from 9 to 13 °C during November. However, both east and west facades decreased daily around variations of 5 °C in the first week of December 2018 with LAI values of 1.5 and 0.7 (Fig. 12). In addition, it is worth remembering that although most leaves fall in the autumn period, many of them remain on the facade along with the trunks and branches. Although the leaves are dead, they still provide a slight shade effect on the building facade at both day and night. (Fig. 14). Maintenance activities during this period maybe could address, if possible, the removal of these dead leaves, in order to avoid this observed non-desired effect.

Fig. 12 also shows the drastic reduction of the cooling effect of the green facade on cloudy days such as on 17, 18, 20, and 23 November. On these days, the daily thermal amplitude between the reference and the double-skin green facade was approximately 4 °C to 7.2 °C in the south, while in the east and west it was no higher than 2 °C.

In order to evaluate the thermal performance of the double-skin green facade in this period, which requires heating to achieve indoor comfort conditions, a set point of 22 °C was established for 13 consecutive days in December (Fig. 13).

In terms of the heat pumps' electrical energy consumption, the results pointed to small daily variations, of about 5.4%, on both the

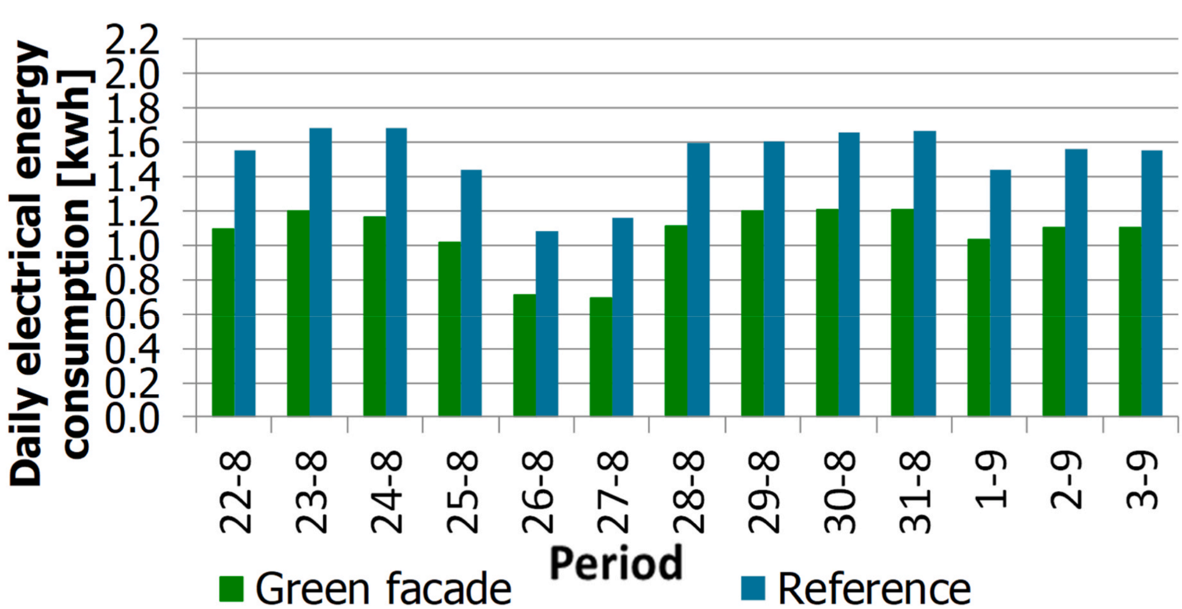

Fig. 11. Daily electrical energy consumption of the heat pumps at 24 °C for cooling purposes. Late summer period of 2018.

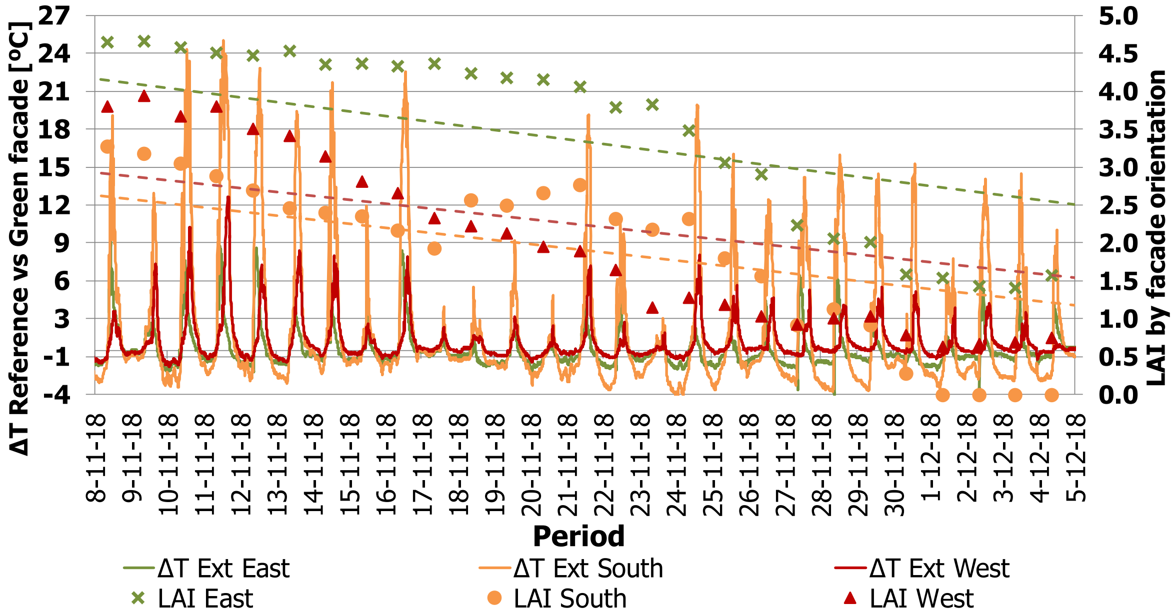

Fig. 12. The evolution of LAI and temperature differences (ΔT) between reference and green facade systems in the autumn period of 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

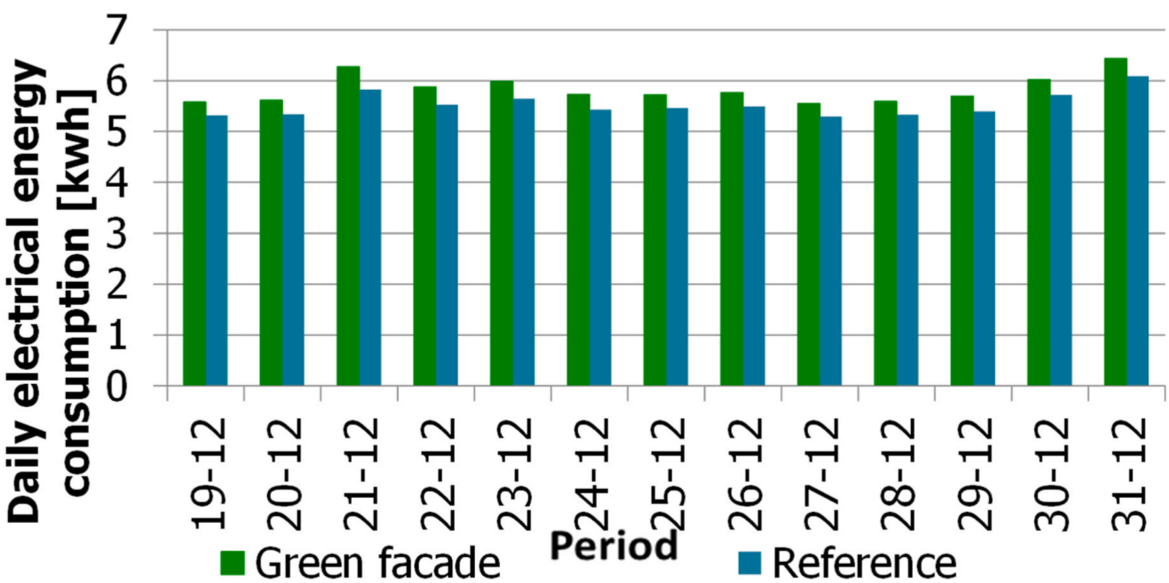

Fig. 13. Daily electrical energy consumption of the heat pumps at 22 °C for heating purposes. Autumn period of 2018.

reference and the double-skin green facade. The accumulated electrical energy consumption over the thirteen consecutive test days was 72.078 kWh and 76.07 kWh, respectively. The small extra energy consumption of the green facade cubicle can be attributed to the reduction in solar gains caused by the permanent trunks and branches as well as unfallen leaves.

As previously mentioned, the plant area index (PAI), a concept that also integrates the contribution of woody material in the foliage density measurements, is very important, especially in deciduous systems. In view of the results obtained in this study, the methodology selected to conduct the LAI study was clearly a success, since by allowing the sensors to record the contribution of branches and unfallen leaves, it was also possible to assess the effect on thermal behaviour during the "leaf-off" stage.

3.2.4. Winter (no leaves)

The winter period encompasses eleven weeks in a Csa climate (warm temperate – summer dry – hot summer), where the south facade receives the highest solar irradiation with a maximum angle of 25.05° at 13:00 h (21 December) that will rise to 48.30° by the spring solstice on 20 March. In this period, the mean LAI values of the double-skin green facade were 1.71, 0.28 and 0.66 for the east, the south and the west facades, respectively.

Notice that from 26 December 2017 to 2 January 2018, there was a fast change of the LAI values caused by a drastic fall process of the leaves, especially on the west and south facades. In these winter days, some of the leaves that still remained on the plants of the east facade, and some of the south facade, had just degraded and fell on specific days of strong wind and/or rain or storm events, causing drastic variations in the LAI on specific days (e.g. 27 December). Fig. 14 includes a period of

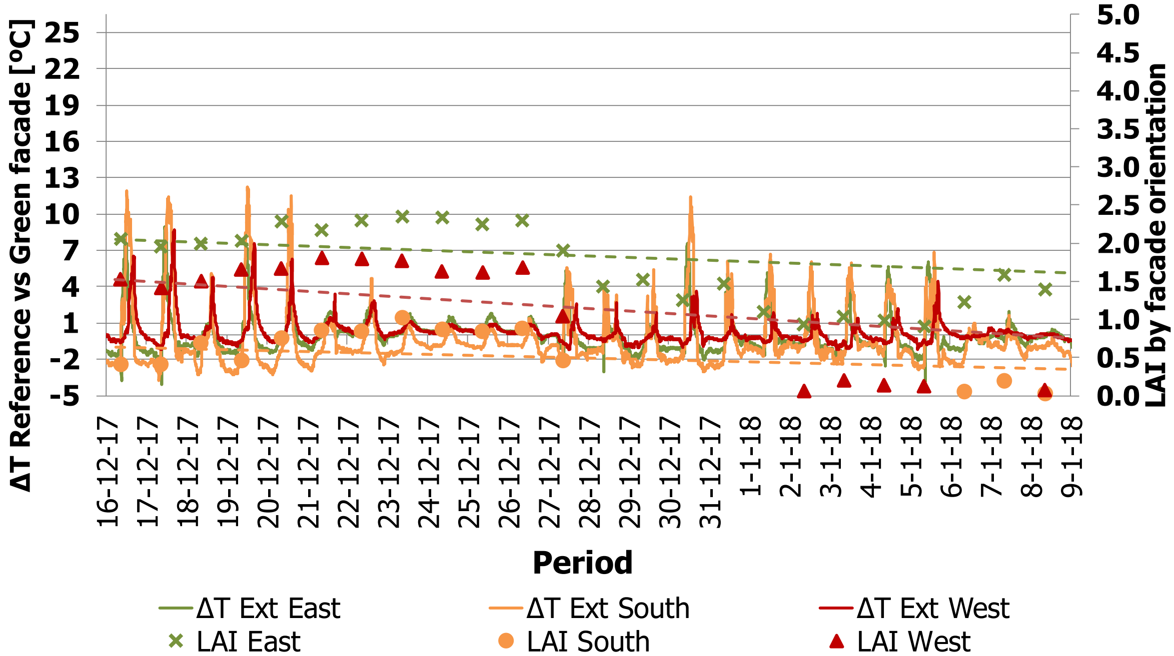

Fig. 14. Evolution of LAI and temperature differences (ΔT) between reference and green facade cubicles in the winter period 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fog (anticyclone) from 23 to 27 December, which ended with the appearance of strong winds, coinciding with the end of the anticyclonic situation, so that on 27 and 28 December, there was the fall of leaves and the drastic change in the LAI, on all three orientations, with special relevance on the eastern side.

Regarding the external surface wall temperatures, Fig. 14 shows the maximum temperature difference of about 12.2 °C between the double-skin green facade and the reference cubicle for a sunny winter day (19 December 2017) on the south facade. Even though the LAI values on the east (2.03) and west (1.65) facades were much higher in comparison to the south (0.46), they registered lower temperature differences of 7.2 °C and 7.6 °C, respectively, because of the lower daily solar irradiation at this time of the year.

During the night after a sunny day, the south, the east, and the west facades were 3.3 °C, 1.6 °C and 0.9 °C warmer than the same facades on the reference cubicle. This thermal behaviour experimentally confirms the reduction of the radiative heat transfer from the walls towards the sky throughout the night (insulation effect), although the incidence in the present experiment, due to the construction system used for the building facade wall, was negligible.

On foggy days from 23 to 26 December 2017, the night radiative insulation effect on the external wall was lower when there was neither direct solar radiation nor indoor heating requirements. However, the night radiative insulation of the double-skin green facade was detected on foggy or very cloudy winter days under heating requirements to achieve the indoor comfort conditions by means of HVAC systems.

With the aim of assessing the thermal performance of the green facade in winter, the indoor air temperatures of both cubicles were set at 22 °C through two uninterrupted weeks in January 2019. The results presented in Fig. 15 show that the daily energy consumption was very similar to the cold period one year before, which provides consistency to the results achieved in this experimental set-up. The double-skin green

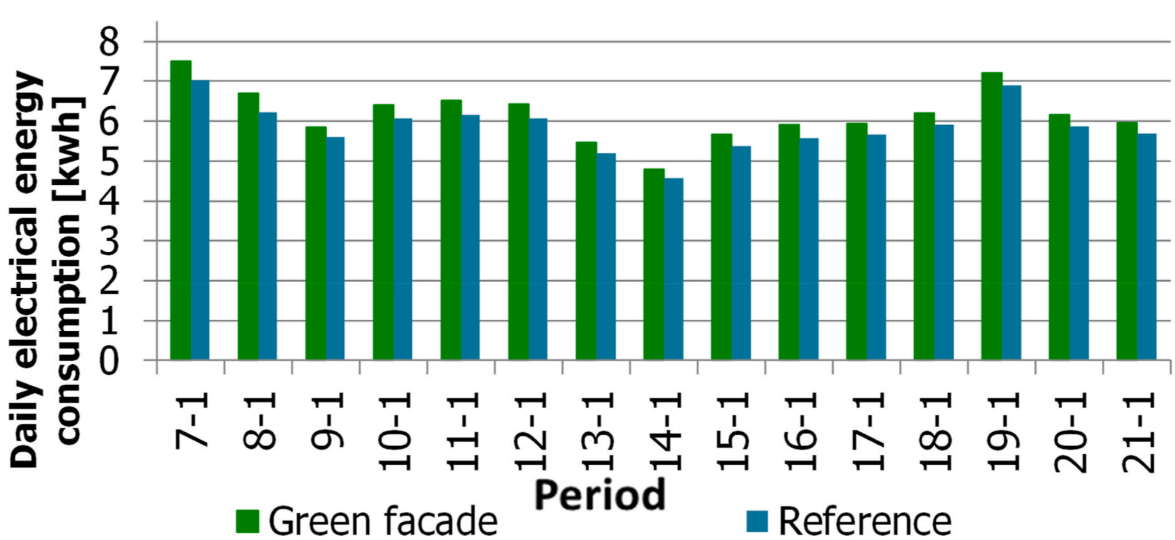

Fig. 15. Daily electrical energy consumption of the heat pumps at 22 °C for heating purposes. Winter period of 2019.

facade and the reference cubicle consumed 93.07 kWh and 88.27 kWh, respectively. Thus, a daily difference of about 5.4% in terms of energy consumption was observed.

3.2.5. Spring (growth)

The growth of Boston ivy leaves was really fast and breathtaking. It took place from the last week of March through the third week of April 2019, which means in just one month, the facade's thermal behaviour completely changed.

Fig. 16 shows the LAI evolution by orientation and the temperature differences (ΔT) between the reference and the green facade cubicles during the transition from winter to spring periods in 2019.

On the east facade, the LAI value ranged from about 1.71 to 4.89, on the south facade the LAI ranged from 0.28 to 4.8, and on the west from 0.66 to 4.74. These values can also be consulted in Table 4 which summarizes all the mean values obtained during the experiment. These increments have the consequent abrupt increase of the ΔT parameter on all the facade orientations in both day and night.

Over the course March 2019, the values of ΔT were above 6 to 9 °C for the west and the east facades and surpassed 11 °C on the south facade, where the sun still had the highest perpendicular incidence on that orientation. Afterwards, as the foliage developed during April, the shade effect on the ΔT parameter, which showed peak values of up to 19 °C and 21 °C on all the orientations, could be perfectly observed.

At night, again the double-skin green facade cubicle showed an increment of the external surface wall temperature in comparison to the reference on all the facades.

Fig. 15 illustrates how, as the LAI increased during March and April, the nighttime ΔT value rose from −1 to -3 °C in March to −3 to -5 °C in April. Evidently, the green screen acted as a thermal barrier between the building wall and the outside. Since this period of year shows the largest daily air temperature oscillations between day and night, the insulation effect of a green facade is more representative than in other seasons, although not enough to have an effect on indoor temperatures, due to the construction system of the building's facade wall (alveolar bricks).

Generally, heating requirements in spring seasons are lower than in winter in the Mediterranean continental climate. However, usually heating is still necessary to maintain the indoor comfort conditions on occasional spring days (March through April). Thus, to evaluate the thermal performance of both the green facade and the reference cubicles during the transition period, an interior set-point temperature of 22 °C was established during two uninterrupted weeks. Fig. 16 shows the daily electrical energy consumption.

Fig. 17 shows the daily electrical energy consumption of the representative spring period of 2019, in which the green facade cubicle consumed 61.4 kWh and the reference consumed 54.2 kWh, representing an 11.9% drop in energy consumption. It can be seen that on cold spring days, the daily consumption of both cubicles, with and without green facade, was balanced, and their thermal performances were similar to those in winter, when the energy consumption of the green facade cubicle was slightly higher (e.g. 21 April). However, on warmer spring days the energy consumption in the green facade cubicle was higher than in the reference one. Thanks to the direct influence of solar radiation on the bare facade walls, the indoor set temperature was achieved faster in the reference cubicle; therefore, it spent less electricity (e.g. 2 May).

Nevertheless, this effect only took place on specific days in the spring, since the heating system hardly ever needs to be activated during May under the climate of study. Moreover, the described effect is of small magnitude in comparison to the total energy consumption for the whole year.

3.2.6. Summary. Influence of LAI on the external wall surface temperatures by façade orientation

Finally, Table 4 summarizes the data obtained during the experiment so that the influence of the evolution of the LAI seasonally on the double-skin green and its consequences on the external surface temperature of the building facade wall can be observed. Table 4 also incorporates the most relevant climatic data during the course of the experiment.

4. Conclusions

The paper presents the characterization of the annual LAI evolution of a double-screen green facade made up of a Boston ivy deciduous climber plant (*Partenocissus tricuspidata*) under Mediterranean continental climate (Csa, warm temperate - summer dry - hot summer), by means of the use of an original non-destructive methodology during two consecutive years. Moreover, the influence of the green facade's foliage density, characterized by LAI, on the external building wall temperatures and the energy consumption by season and orientation (east, south

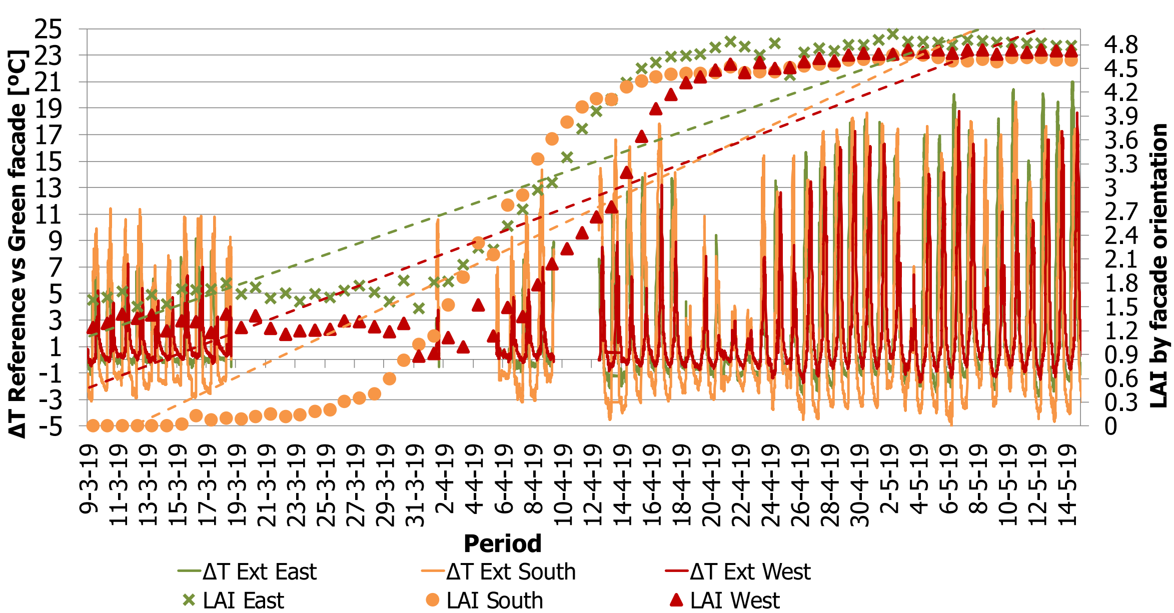

Fig. 16. Evolution of LAI and temperature differences (ΔT) between reference and green facade systems in the spring period of 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Seasonal leaf area index (LAI) influence on the external wall surface temperatures by facade orientation.

		Early summer (full coverage)	Late summer (degraded foliage)	Autumn (fall)	Winter (no leaves)	Spring (growth)
East orientation	**Avg. LAI [m^2/m^2]**	4.89	4.72	2.43	1.71	3.85
	Avg. ΔT [°C]	4.5	3.0	0.1	0.0	1.7
	Max. ΔT [°C]	21.0	20.0	10.6	9.4	18.1
	Min. ΔT [°C]	−2.0	−2.5	−3.6	−5.5	−2.6
South orientation	**Avg. LAI [m^2/m^2]**	4.80	4.12	1.10	0.28	3.77
	Avg. ΔT [°C]	4.1	5.1	0.8	−0.3	2.0
	Max. ΔT [°C]	21.8	26.7	24.5	17.0	18.6
	Min. ΔT [°C]	−3.6	−6.2	−3.6	−4.9	−4.5
West orientation	**Avg. LAI [m^2/m^2]**	4.74	4.42	1.45	0.66	3.19
	Avg. ΔT [°C]	3.5	2.7	0.6	0.5	1.7
	Max. ΔT [°C]	20.4	19.2	13.2	10.4	17.3
	Min. ΔT [°C]	−1.3	−1.6	−1.3	−2.3	−1.8
Cubicle	**Avg. LAI [m^2/m^2]**	4.8	4.4	1.7	0.9	3.6
	Avg. ΔT [°C]	4.0	3.6	0.5	0.1	1.8
	Daily energy savings	54% cooling	30% cooling	−5.4% heating	−5.4% heating	−11.9% heating
Weather conditions	**Min. temp [°C]**	8.6	3.4	−5.1	−8.2	0.1
	Max. temp [°C]	37.8	40.4	23.9	21.2	26.0
	Avg. temp [°C]	22.8	21.6	7.4	5.45	13.5
	Avg. Solar radiation [W/m^2]	533.8	456.4	180.5	195.2	453.5
	Avg. RH [%]	64.9	70.2	89.8	79.6	68.2

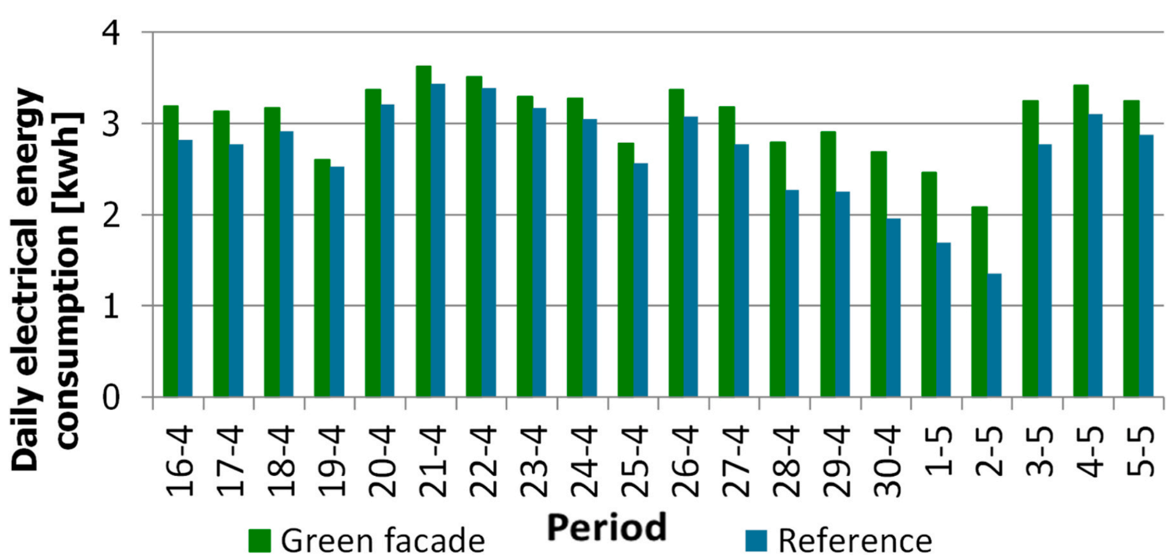

Fig. 17. Daily electrical energy consumption of the heat pumps at 22 °C for heating purposes. Spring period of 2019.

and west facades) was addressed.

The main conclusions derived from this innovative research project are the following:

- Annual evolution of LAI: five different periods can be clearly differentiated, which are early summer (full new leaf; LAI of 4.8), late summer (degraded foliage; LAI of 4.4), autumn (fall; LAI of 1.7), winter (without leaves; LAI of 0.9), and spring (growth; LAI of 3.6) (Fig. 7 and Table 4).
- This evolution of the LAI has a direct influence on the external surface temperatures of the building facade wall as well as on the daily energy consumption: early summer (avg. ΔT [°C] of 4.0 and daily energy savings of 54%), late summer (avg. ΔT [°C] of 3.6 and daily energy savings of 30%), autumn (avg. ΔT [°C] of 0.5 and daily energy savings of −5.4%), winter (avg. ΔT [°C] of 0.1 and daily energy savings of −5.4%), and spring (avg. ΔT [°C] of 1.8 and daily energy savings of −11.9%).
- The great potential of double-skin green facades to provide passive energy savings during cooling periods was confirmed, reaching 54% reductions in daily energy consumption in early summer (May-June-July) and 30% during late summer (August-September-October).
- During the "leaf-off" stage (autumn and winter), the contribution of woody material in the foliage density measurements accounted for an increment of 5.4% in the daily energy consumption for heating.
- These results exemplified the importance of considering the whole year when the thermal performance of a VGS is studied.
- The impact of facade orientation was confirmed, showing not only differentiated foliage development but also different impacts on energy performance, characterized by the external surface temperatures of the building facade walls (Table 4).
- At night, an insulation effect was clearly identified. The green screen acts as a real insulating barrier, reducing the radiative heat transfer through the walls into the sky at night.

This study highlights the importance of considering the specific micro-climate and the orientation of each architectural project when working with VGSs. Thus, orientation to sun exposure as well as to prevailing winds or breezes can condition the seasonal dynamics of plants (growth, leaf fall, etc.) and, in turn, their thermal behaviour.

The methodology used for the continuous measurement of LAI has been shown to be robust, successful, and easy to implement and replicate around the world. The method not only provided an accurate description of LAI evolution through the year, but also allow describing the contribution of branches and unfallen leaves during the "leaf-off" stage. Consequently, it is suggested to be used by the scientific community in the future to obtain comparable results from different plant species and under different climates. However, some limitations such as the availability of the necessary sensors to measure NVDI and the support structure to place them at certain distance from away from the green screen, as well as the need to carry out specific measurements in periods of rapid change of LAI in order to verify the relationship between the NVDI and LAI index, should be taken into account in future equivalent research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors at GREiA research group would like to thank the Catalan Government for the quality accreditation given to their research group (2017 SGR 1537). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme.

References

[1] United Nations, sustainable development goals. Knowledge platform. https://sustainabledevelopment.un.org/sdgs.
[2] J. Coma, J.M. Maldonado, A. de Gracia, T. Botargues, L.F. Cabeza, Comparative analysis of energy demand and CO_2 emissions on different typologies of residential buildings in Europe, Energies 12 (12) (2019) 2436, https://doi.org/10.3390/en12122436.
[3] European Commission. Towards an EU research and innovation policy agenda for 'Nature-based Solutions and Re-naturing Cities', 2015. Final Report of the Horizon 2020. Expert group on 'Nature-based Solutions and Re-naturing Cities'.
[4] G. Pérez, K. Perini, Nature Based Strategies for Urban and Building Sustainability, Elsevier, Imprint, 2018. Butterworth-Heinemann. eBook ISBN: 9780128123249. Paperback ISBN: 9780128121504.
[5] J. Coma, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, L.F. Cabeza, Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades, Build. Environ. 111 (2017) 228–237, https://doi.org/10.1016/j.buildenv.2016.11.014.
[6] L.L.H. Peng, Z. Jiang, X. Yang, Q. Wang, Y. He, S.S. Chen, Energy savings of block-scale facade greening for different urban forms, Appl. Energy 279 (2020) 115844, https://doi.org/10.1016/j.apenergy.2020.115844.
[7] G. Pérez, J. Coma, I. Martorell, L.F. Cabeza, Vertical Greenery Systems (VGS) for energy saving in buildings: a review, Renew. Sustain. Energy Rev. 39 (2014) 139–165, https://doi.org/10.1016/j.rser.2014.07.055.
[8] R. Bustami, M. Belusco, J. Ward, S. Beecham, Vertical greenery systems: a systematic review of research trends, Build. Environ. 146 (2018) 226–237, https://doi.org/10.1016/j.buildenv.2018.09.045.
[9] T. Suklje, M. Hamdy, C. Arkar, J.L.M. Hensen, S. Medved, An inverse modeling approach for the thermal response modeling of green façades, Appl. Energy 235 (2019) 1447–1456, https://doi.org/10.1016/j.apenergy.2018.11.066.
[10] L.S.H. Lee, C.Y. Jim, Energy benefits of green-wall shading based on novel-accurate apportionment of short-wave radiation components, Appl. Energy 238 (2019) 1506–1518, https://doi.org/10.1016/j.apenergy.2019.01.161.
[11] G. Vox, I. Blanco, E. Schettini, Green façades to control wall surface temperature in buildings, Build. Environ. 129 (2018) 154–166, https://doi.org/10.1016/j.buildenv.2017.12.002.
[12] S. Poddar, D. Park, S. Chang, Energy performance analysis of a dormitory building based on different orientations and seasonal variations of leaf area index, Energy Efficiency 10 (2017) 887–903, https://doi.org/10.1007/s12053-016-9487-y.
[13] G. Pérez, J. Coma, S. Sol, L.F. Cabeza, Green facade for energy savings in buildings: the influence of leaf area index and façade orientation on the shadow effect, Appl. Energy 187 (2017) 424–437, https://doi.org/10.1016/j.apenergy.2016.11.055.
[14] I. Susorova, M. Angulo, P. Bahrami, B. Stephens, A model of vegetated exterior facades for evaluation of wall thermal performance, Build. Environ. 67 (2013) 1–13, https://doi.org/10.1016/j.buildenv.2013.04.027.
[15] G. Pérez, L. Rincón, A. Vila, J.M. Gonzalez, L.F. Cabeza, Green vertical systems for buildings as passive systems for energy savings, Appl. Energy 88 (2011) 4854–4859, https://doi.org/10.1016/j.apenergy.2011.06.032.
[16] G. Pérez, L. Rincón, A. Vila, J.M. Gonzalez, L.F. Cabeza, Behaviour of green façades in Mediterranean Continental climate, Energy Convers. Manag. 52 (2011) 1861–1867, https://doi.org/10.1016/j.enconman.2010.11.008.
[17] C.Y. Jim, Thermal performance of climber greenwalls: effects of solar irradiance and orientation, Appl. Energy 154 (2015) 631–643, https://doi.org/10.1016/j.apenergy.2015.05.077.
[18] G. Pérez, "*Façanes vegetades. Estudi del seu potential com a sistema passiu d'estalvi d'energia, en clima mediterrani continental*", PhD thesis, Universitat Politècnica de Catalunya, 2010, http://hdl.handle.net/2117/93456.
[19] D.J. Watson, Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties and within and between years, Ann. Bot. 11 (1947) 41–76.
[20] A.R.G. Lang, X. Yueqin, J.M. Norman, Crop Structure and the penetration of direct sunlight, Agric. For. Meteorol. 35 (1985) 83–101.
[21] I. Jonckheere, S. Fleck, K. Nackaerts, B. Muys, P. Coppin, M. Weiss, F. Baret, Review of methods for in situ leaf area index determination Part I. Theories, sensors and hemispherical photography, Agric. For. Meteorol. 121 (2004) 19–35.
[22] G.S. Campbell, J.M. Norman, An Introduction to Environmental Biophysics, Springer, 1998, ISBN 0-387-94937-2.
[23] LAI theory and practice. Decagon Devices. www.decagon.com, 2014.
[24] T.S. Magney, J.U.H. Eitel, D.R. Huggins, L.A. Vierling, Proximal NDVI derived phenology improves in-season predictionsof wheat quantity and quality, Agric. For. Meteorol. 217 (2016) 46–60, https://doi.org/10.1016/j.agrformet.2015.11.009.
[25] T.N. Carlson, D.A. Ripley, On the relation between NDVI, fractional vegetation cover, and leaf area index, Rem. Sens. Environ. 62 (Issue 3) (December 1997) 241–252, https://doi.org/10.1016/S0034-4257(97)00104-1.
[26] Y. Guangjian, H. Ronghai, L. Jinghui, W. Marie, J. Hailan, M. Xihan, X. Donghui, Z. Wuming, Review of indirect optical measurements of leaf area index: recent advances, challenges, and perspectives, Agric. For. Meteorol. 265 (2019) 390–411, https://doi.org/10.1016/j.agrformet.2018.11.033.
[27] Alvaro de Gracia Lidia Navarro Julià Coma Susana Serrano Joaquim Romaní Gabriel Pérez Luisa F Cabeza, Experimental set-up for testing active and passive systems for energy savings in buildings – lessons learnt, Renew. Sustain. Energy Rev. 82 (1) (February 2018) 1014–1026, https://doi.org/10.1016/j.rser.2017.09.109.
[28] Köppen-Geiger climate classification. http://koeppen-geiger.vu-wien.ac.at/.
[29] Fassadenbegrünungsrichtlinien - Richtlinien für die Planung Bau und Instandhaltung von Fassadenbegrünungen, Forschungsgesellschaft landschaftsentwicklung landschaftsbau (FLL). https://www.fll.de/, 2018.
[30] NTJ-11V Ajardinamientos verticales. Normas Tecnológicas de jardinería y paisajismo. Fundació de la Jardineria i el Paisatge. https://www.ntjdejardineria.org/.
[31] SQ-311-SS: sun calibration original line Quantum with 10 sensors. https://www.apogeeinstruments.com/sq-311-ss-sun-calibration-original-line-quantum-with-10-sensors/.
[32] American Society of Heating, Refrigerating and air conditioning engineers, inc., Ashrae handbook fundamentals, in: R.A. Parsons (Ed.), Nonresidential Cooling and Heating Load Calculations, 1997 (pp. 28.7e28.16). Atlanta: SI Edition.
[33] E. Rodrigues, M. Fernandes, Overheating risk in Mediterranean residential buildings: comparison of current and future climate scenarios, Appl. Energy 259 (2020) 114110, https://doi.org/10.1016/j.apenergy.2019.114110.
[34] Riley Benjamin, The state of the art of living walls: lessons learned, Build. Environ. 114 (2017) 219–232, https://doi.org/10.1016/j.buildenv.2016.12.016.